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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 802

TESTS OF A GUST-ALLEVIATING WING IN THE GUST TUNNEL

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By C. C. Shufflebarger

SUMMARY

Tests were made in the NACA gust tunnel to determine the effectiveness of a torsionally flexible wing with the torsion axis ahead of the locus of the section aerodynamic centers in reducing airplane accelerations due to atmospheric gusts. For three gust shapes, a series of flights was made with the airplane model equipped with either a torsionally flexible or a rigid wing.

The results indicated that the torsionally flexible wing reduced the maximum acceleration increment 5 percent for the sharp-edge gust and about 17 percent for gust shapes with gradient distances of 6.8 and 15 chord lengths. The analysis indicated that the effectiveness of this method of gust alleviation was independent of the gust velocity and that, for the same total load increment, the torsionally flexible wing would have 10 percent less bending-moment increment at the root section of the wing than a rigid wing in all but the sharpest gusts. The results also indicated that the torsionally flexible wing slightly increased the longitudinal stability of the airplane model in a gust.

INTRODUCTION

Two devices that depend upon the use of a trailing-edge flap for alleviating the loads on airplanes due to gusts have been tested. One device (reference 1) depends upon the vertical displacement of the airplane to operate the flap; the other device (reference 2) depends upon an auxiliary airfoil to operate the flap. Both these devices are of a mechanical nature and are therefore not so reliable as a method that makes use of the inherent elastic properties of the airplane structure. A method that makes use of the inherent elastic properties of the wing for the alleviation of gust loads results when the torsion axis of a wing of low torsional rigidity is located ahead of the

locus of the section aerodynamic centers. In this arrangement increasing loads on the wing cause increasing washout, which reduces the total load on the wing and the bending moment at the wing root. An advantage of this method over the method tested in reference 1 is that the functioning of the arrangement is dependent upon the load on the wing instead of the displacement of the airplane, which may be small when the load is high. The practical application of such a method would involve questions of reversal of control and flutter with conventional ailerons; consideration of these points indicates that some form of leading-edge lateral control will be necessary.

When the present investigation was undertaken, tests of a promising leading-edge lateral-control system were being made. Inasmuch as this control did not meet expectations, the use of the method of gust alleviation reported herein must await the development of a satisfactory lateral-control system. Even if this difficulty were overcome by the development of a satisfactory lateral-control system, however, present design trends tend to make this system impracticable.

This paper presents the results of tests of an airplane model equipped with a wing in which the alleviation of gust loads was obtained by torsional deflection. The tests were made with three gust shapes in the NACA gust tunnel during the summer of 1939.

APPARATUS AND TESTS

The gust tunnel and the auxiliary equipment have been described in reference 3. The gust shapes used during the investigation are shown in figure 1.

The pertinent characteristics of the airplane model (figs. 2 and 3) that was used in the tests are given in table I. When the model was flown, it was equipped with either of two wings. One wing was of low torsional rigidity (flexible wing) and the torsion axis was located at 10 percent of the chord. The other wing was like the first one except that it had a higher torsional rigidity (rigid wing) and its torsion axis was located at approximately 25 percent of the chord. Both wings were covered with thin sheet rubber, the purpose of which was to obtain low torsional rigidity with one wing and to have comparable

surfaces on the two wings. Details of the structure of the flexible wing are shown in figure 4. The leading edge of the wing was cut in the chord direction at frequest stations and was braced in the drag direction by struts with ball-and-socket joints at each end.

The twist curve for the flexible wing under a load-factor increment of 1.0 is shown in figure 5. This curve was obtained by distributing the load along the 25-percent-chord points in such a manner as to take into account the effect of the twist and the wing mass on the span loading. A similar curve is not given for the rigid wing because, under normal loadings, the rigid wing was found to have negligible twist.

The measured fundamental period of the flexible wing in torsion is listed in table I. Similar measurements are given for the rigid wing.

Because all computations were based on a wing rigid in bending, the flexible wing was made as rigid in bending as feasible. In order to obtain a measure of the wing rigidity, the static-wing deflection curves and the natural periods of the two wings in bending were experimentally determined. The natural periods of the wings in bending are given in table I and the static-wing deflection curves in bending for a load factor of 1.0 (loading proportional to the chord) are shown in figure 6.

In addition to the usual measurements of pitch, acceleration increment, and speed, the vertical displacements of two stations along the chord of the wing tip were recorded during passage through the gust. This measurement was made by recording the vertical displacements of two small lamps, mounted forward and rearward along the chord of the wing tip, on the accelerometer film as shown in figure 7. Any movement of one lamp relative to the other lamp served as a direct measurement of the wing twist. Owing to the method of recording the motion, the record of the tip motion A shown in figure 8 is offset on the film from the acceleration record B.

Interference of the diagonal drag braces with the wing ribs under load increments greater than 1.25g required a restriction of the gust velocities used in the tunnel to values that gave increments less than the foregoing value.

The test procedure consisted in flying the model,

equipped with either the flexible or the rigid wing, over the gust tunnel under similar conditions. The tests were made for gust-gradient distances of 1, 5.8, and 15 chord lengths, one nominal forward velocity, and one value of the wing loading. The velocities and the wing loading used are included in table I; the gust shapes are shown in figure 1. Five or more flights were made for each condition to obtain mean values of the acceleration increment.

RESULTS

The records obtained during the tests were evaluated to give histories of events during entry into and traverse of the gust. Sample histories of uncorrected results for repeat flights for each of the test conditions are shown in figures 9, 10, and 11.

The maximum acceleration increment for each run was corrected to a forward velocity of 60 feet per second and to a gust velocity of 6.0 feet per second. This correction was made on the assumption that the acceleration increment varied directly with the gust velocity and the forward speed. (Experimental verification of this assumption is shown in reference 3.) The actual gust velocities used for each gust-gradient distance are included in table I. The corrected acceleration increments are shown in figure 12 for both the flexible-wing and the rigid-wing models as a function of the gust-gradient distance.

The wing effectiveness, defined as the percentage reduction in acceleration increment due to the wing flexibility, was computed for each gust-gradient distance from the data of figure 12 and is shown in figure 13.

PRECISION

The measured quantities for any run are estimated to be accurate within the following limits:

Acceleration increment - - - - - - - - - - - - - ±0.1g

Forward velocity - - - - - - - - - ±1.0 foot per second

Gust velocity - - - - - - - - - - - ±0.1 foot per second

Pitch-angle increment - - - - - - - - - - - - - - - ±0.2°

Twist of wing tip - - - - - - - - - - - - - - - - - - ±0.2°

In addition to direct errors of measurement, there exist indirect errors resulting from oscillations of the airplane model after it left the catapult. In the discussion of reference 4 it is indicated that these errors have a negligible effect on the acceleration increment although they may have a large effect on the measured pitch displacement of the model in a long gradient gust.

An approximate calculation based on the natural period in bending (table I) and the wing-deflection curves of figure 6, indicated an error in acceleration increment of not more than 1.5 percent due to the flexibility of the wings in bending. This error is felt to be well within the accuracy of the other measurements.

The effectiveness of the flexible wing in reducing the maximum acceleration increment, as determined from the test results, is estimated to be accurate within ±0.04g.

DISCUSSION

As shown by the angle-of-pitch curves in the sample time histories (figs. 9, 10, and 11) the flexible wing had a small but favorable effect on the longitudinal stability in a gust. Calculations made in a manner similar to those of reference 4, but which included the effect of downwash, also bore out this trend toward increased stability.

The results of figure 13 indicate that the alleviation of the gust load by this method amounts to approximately 17 percent in the case of the longer gust-gradient distances; whereas, for the shortest one tested, the alleviation is only 5 percent. The smaller reduction in the case of the shortest gradient distance is primarily due to the fact that the time of application of the load was such that the wing twist was not directly proportional to the acceleration. (For example, in fig. 9, when acceleration has reached 50 percent of its maximum value, the wing twist is only 27 percent of its maximum.) Rough calculations indicate that, in order for the wing twist to be directly proportional to the applied load, the time of application of the load increment, from zero to maximum

(0.03 to 0.14 sec for gust shapes used), must be greater than the natural torsional period of the wing (table I, 0.0562 sec). In the present case this condition would be fulfilled for gust-gradient distances greater than 6 chord lengths. Practically, the small alleviation obtained in the shortest gradient gust is of small consequence because present knowledge indicates that gusts of small gradient distances are of small intensity.

Calculations made according to the method outlined in the appendix indicated that, for the ideal case where the wing twist is proportional to the acceleration increment, the wing effectiveness in alleviating the loads due to gusts would decrease slightly with an increase in the gradient distance and would be independent of the gust velocity. The solid line of figure 13 gives the results of the computations for this case. As previously pointed out, however, the lag of the wing altered the response of the system in the shortest gust-gradient distances so that the results given by the dashed line of figure 13 are applicable to the case tested when the wing lagged. It can be seen that the experimental points are in fair agreement with these computations.

In addition to reducing the total load, the flexible wing changes the span load distribution so that the bending moment at the wing root is less than that for a rigid wing with the same total load increment. Computations indicated that, for the airplane model used with a wing twist equivalent to about 3° linear twist per unit load factor, the bending-moment increment at the wing root would be reduced by approximately 10 percent. This value applies only when the twist is proportional to the load increment.

As previously mentioned, the practical application of this method of gust alleviation to an airplane would raise many serious questions, the most important of which would probably be questions of flutter and reversal of aileron control. It is well known that, with a wing of low torsional rigidity, the use of a flap control such as the conventional aileron may cause a reversal of lateral control.

A leading-edge lateral-control system would reduce, if not eliminate, the twisting moment due to the lateral-control system. Present design practices, such as the use of conventional high-lift devices and the location of en-

gine nacelles, fuel tanks, and other equipment in the wings, would likewise make a higher torsional rigidity necessary and thereby reduce the effectiveness of the wing. In the absence of a satisfactory leading-edge control and with present trends, it is felt that the method of alleviating gust loads by torsional deflection of the wing would not be a practicable one.

CONCLUDING REMARKS

For the airplane model tested, the results indicated that the torsionally flexible wing reduced the maximum acceleration increment 5 percent for a sharp-edge gust and about 17 percent for gust shapes with gradient distances of 6.8 and 15 chord lengths. The analysis indicated that the small reduction of the acceleration increment in a sharp-edge gust was due to the lagging of the acceleration by the wing twist and that the wing effectiveness was independent of the gust velocity. Computations also indicated that, for the same total load increment, the torsionally flexible wing would have 10 percent less bending-moment increment at the wing root section than a rigid wing in all but the sharpest gusts. Both computation and experiment indicated that the torsionally flexible wing slightly increased the longitudinal stability in a gust.

In the absence of a satisfactory leading-edge control and with present trends, it is felt that the method of alleviating gust loads by torsional deflection of the wing would be impracticable.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 5, 1941.

APPENDIX

Computation of Wing Effectiveness

The computations for the wing effectiveness were made with the following assumptions:

1. The acceleration increment is a linear function of the distance penetrated in a linear gradient gust.

2. The twist of the wing at any station varies directly with the acceleration increment of the airplane model.

3. The pitch of the airplane model is negligible to peak acceleration.

4. Whether the wing is flexible or rigid, the maximum value of acceleration increment will occur at the same distance from the start of the gust. (See equations (3) and (4) of reference 5.)

5. The effect of the wing twist can be represented by an equivalent change of angle of attack of the wing.

6. The model can be considered as consisting of a wing only.

7. The wing is rigid in bending.

The equation for Δn, the maximum acceleration increment, is then:

$$\Delta n = \frac{dC_L}{d\alpha}\frac{Sq}{W}\frac{l}{V}\int_0^{s_1} C_{L_g}(s_1 - s)\frac{dU}{ds}\,ds - \frac{dC_L}{d\alpha}\frac{Sq}{W}\frac{c}{V}\frac{l}{V}\frac{\Delta n}{s_1}\int_0^{s_1} C_{L_\alpha}(s_1 - s)\,s\,ds - \frac{dC_L}{d\alpha}\frac{Sq}{W}\int_0^{s_1} C_{L_\alpha}(s_1 - s)\frac{d\alpha_t}{ds}\,ds \qquad (1)$$

where

Δn acceleration increment at the point of maximum gust velocity for a linear gradient gust

S wing area

q dynamic pressure

W airplane weight

$\frac{dC_L}{d\alpha}$ slope of wing lift curve per radian

V forward velocity (assumed constant)

c mean geometric chord of wing

U gust velocity at any point

C_{L_g} unsteady-lift function for an airfoil penetrating a sharp-edge gust (reference 5)

s distance airplane has penetrated into gust, chord lengths

s_1 gradient distance, chord lengths

C_{L_α} unsteady-lift function for a sudden change of angle of attack for infinite aspect ratio

$C_{L_\alpha} = 1 - \frac{1}{2 + s}$ (derived fron equation (1a), reference 7)

α_t effective change of angle of attack due to twist of wing

and

K_1, K_2, and K_3 constants

Subscripts:

F flexible wing

R rigid wing

The first two terms of equation (1) represent those of equation (1) of reference 1, the first term being identical and the second term being derived by substituting for K_1 and $\Delta n(s)$ their values c/V and $\frac{\Delta n}{s_1}s$, respectively. These two terms represent the acceleration increment for a model with a rigid wing. For a particular case:

$$\Delta n_R = \Delta n_o - K_1 \Delta n_R$$

$$\Delta n_R = \frac{\Delta n_o}{1 + K_1}$$

where Δn_o represents the first term of equation (1) and $K_1 \Delta n_R$ the second term with Δn replaced by Δn_R.

The third term of equation (1) is easily solved if the wing twist is assumed to be directly proportional to the acceleration increment (assumption 2). Then α_t is proportional to Δn (assumption 5), so that

$$\alpha_t = K_2 \frac{\Delta n}{s_1} s \quad \text{and} \quad \frac{d\alpha_t}{ds} = K_2 \frac{\Delta n}{s_1}$$

Substitute in the third term of equation (1) and perform the indicated operation. The third term is equal to $K_3 \Delta n$ for a particular case and

$$\Delta n_F = \Delta n_o - K_1 \Delta n_F - K_3 \Delta n_F$$

or

$$\Delta n_F = \frac{\Delta n_o}{1 + K_1 + K_3}$$

The wing effectiveness is therefore equal to

$$100 \left(\frac{\Delta n_R - \Delta n_F}{\Delta n_R} \right) = 100 \left(1 - \frac{1 + K_1}{1 + K_1 + K_3} \right)$$

When the period of the imposed acceleration (considered here to be twice the time from zero to peak acceleration) is less than twice the torsional period of the wing, the wing twist will no longer be directly propor-

tional to the acceleration owing to lag of the wing motion. When assumption 2 did not hold (wing motion lagged the acceleration) and for the shorter gust-gradient distances where assumption 1 was not true, the analysis was made as follows:

1. The motion of the wing was computed for unit acceleration, the torsional frequency of the wing and the frequency of the imposed acceleration (determined from assumption 4) being taken into account. Methods of computing the motion may be found in any good textbook on vibration. For the case of the sharp-edge gust where assumption 1 does not hold, the shape of the acceleration curve was represented by $1 - 1 \cos pt$ where t is the time in seconds after the entry into the gust and $p = 4\pi V \div$ (distance to peak acceleration).

2. The third term of equation (1) is solved graphically as in reference 4 for the motion of the wing for unit acceleration. The resulting value is equal to K_2 and the wing effectiveness is found as before.

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1. Donely, Philip, and Shufflebarger, C. C.: Tests of a Gust-Alleviating Flap in the Gust Tunnel. T.N. No. 745, NACA, 1940.

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3. Donely, Philip: An Experimental Investigation of the Normal Acceleration of an Airplane Model in a Gust. T.N. No. 706, NACA, 1939.

4. Donely, Philip, Pierce, Harold B., and Pepoon, Philip W.: Measurements and Analysis of the Motion of a Canard Airplane Model in Gusts. T.N. No. 758, NACA, 1940.

5. Rhode, Richard V.: Gust Loads on Airplanes. SAE Trans., vol. 32, 1937, pp. 81-88.

6. Wagner, Herbert: Über die Entstehung des dynamischen Auftriebes von Tragflügeln. Z.f.a.M.M., Bd. 5, Heft 1, Feb. 1925, pp. 17-35.

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TABLE I

Characteristics of Airplane Model

	Model		Hypothetical airplane with flexible wing
	With rigid wing	With flexible wing	
Weight, pounds	1.55	1.55	21,400
Wing area, square feet	1.71	1.71	985
Wing loading, pounds per square foot	.91	.91	21.8
Span, feet	3.05	3.05	73.2
Mean geometric chord, feet	.562	.562	13.5
Center of gravity, percent mean geometric chord	25	25	25
Fundamental wing period, seconds:			
Bending	.0217	.0127	.106
Torsion	.0562	(a)	.275
Moment of inertia, mk_Y^2, slug-feet^2	.0115	.0115	91,500
Gust velocity, feet per second:			
1-chord-length gust	3.83	3.91	18.8
6.8-chord-length gust	4.33	4.55	21.2
15-chord-length gust	6.70	7.06	32.8
Forward velocity, feet per second	60.0	58.0	294

[a]Approximately same as value in bending.

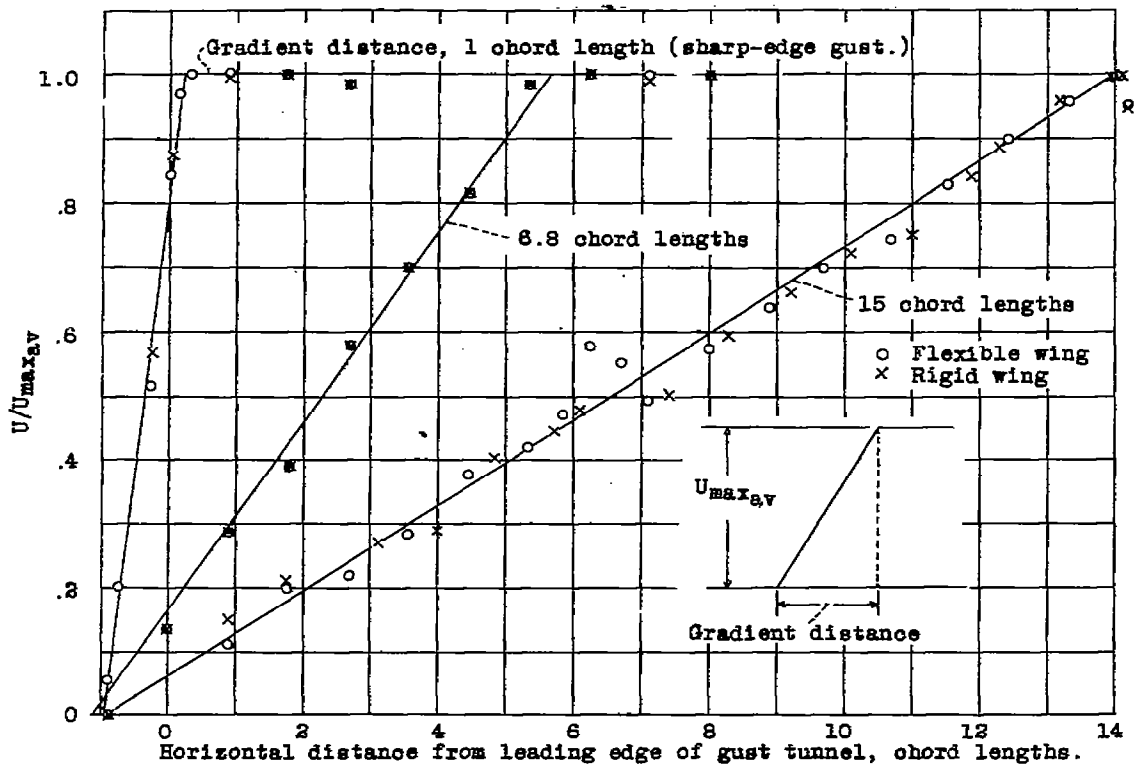


Figure 1.- Velocity distribution through jet.

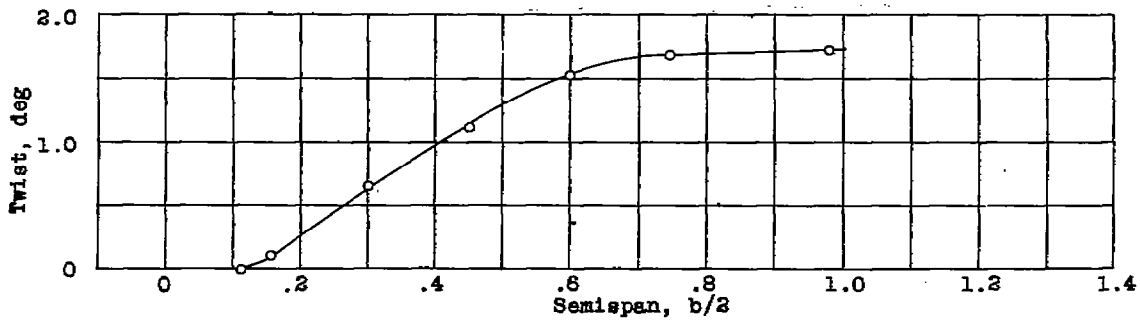


Figure 5.- Wing-twist increment. Load-factor increment, 1.0; flexible wing.

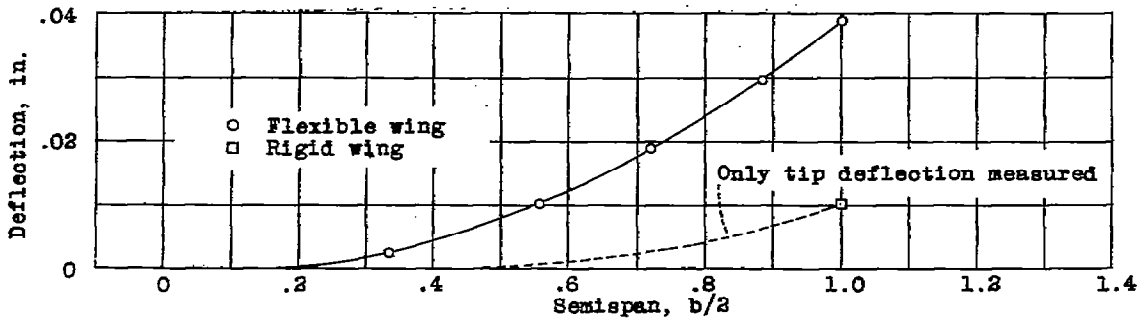


Figure 6.- Static-wing deflection curves. Load factor, 1.0.

Figure 2.- Airplane model.

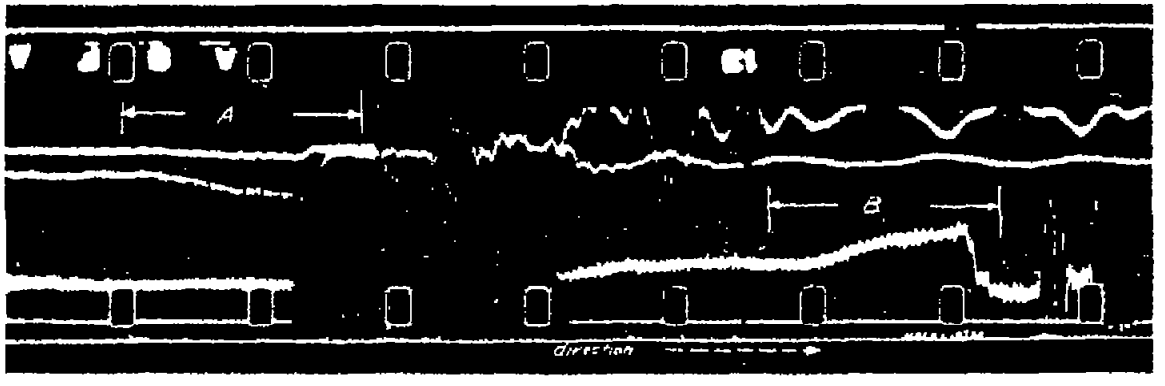


Figure 8.- Portion of accelerometer film showing: A. Record of wing-tip motion in the B. Record of acceleration in the gust.

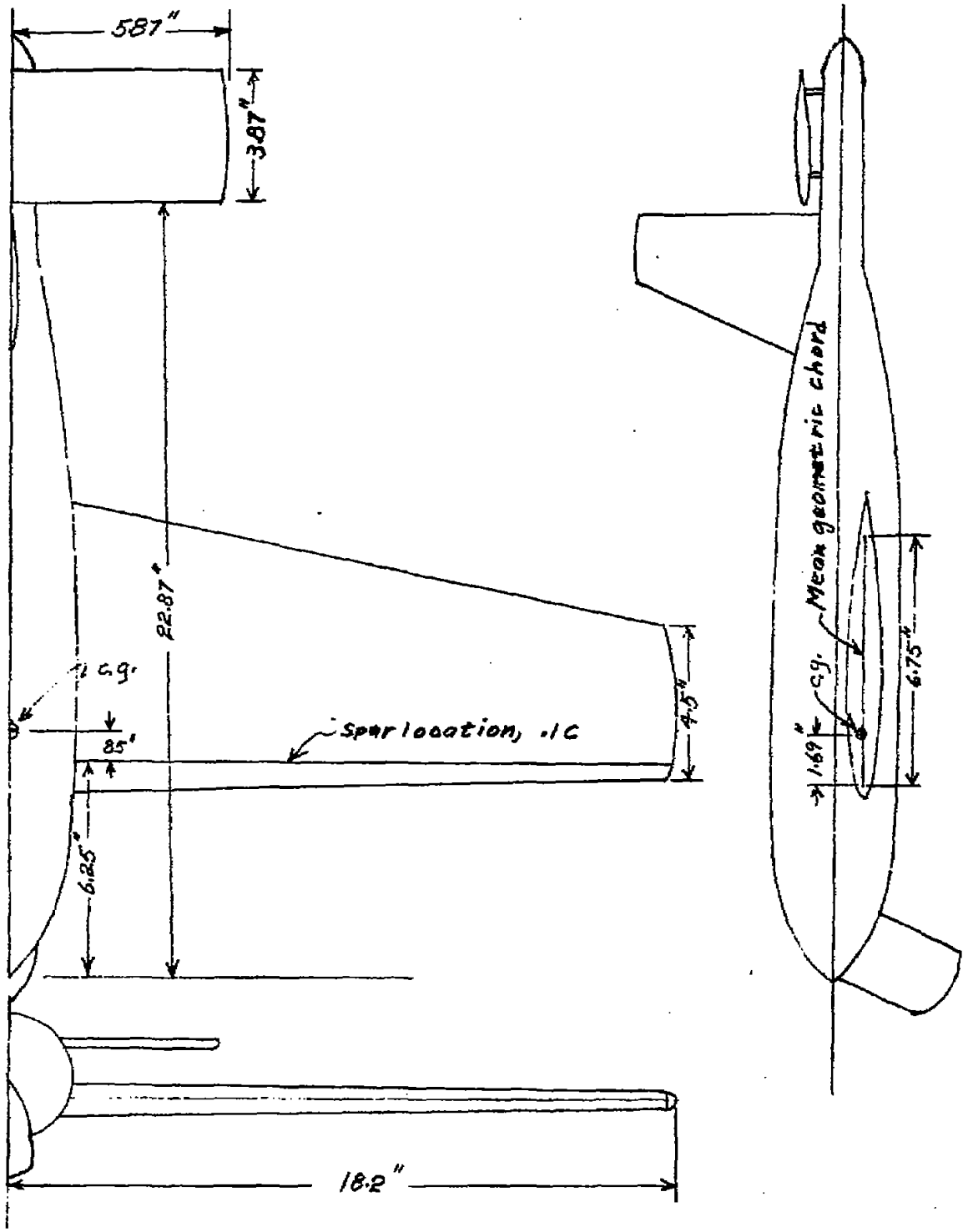


Figure 3.- Line drawing of airplane model.

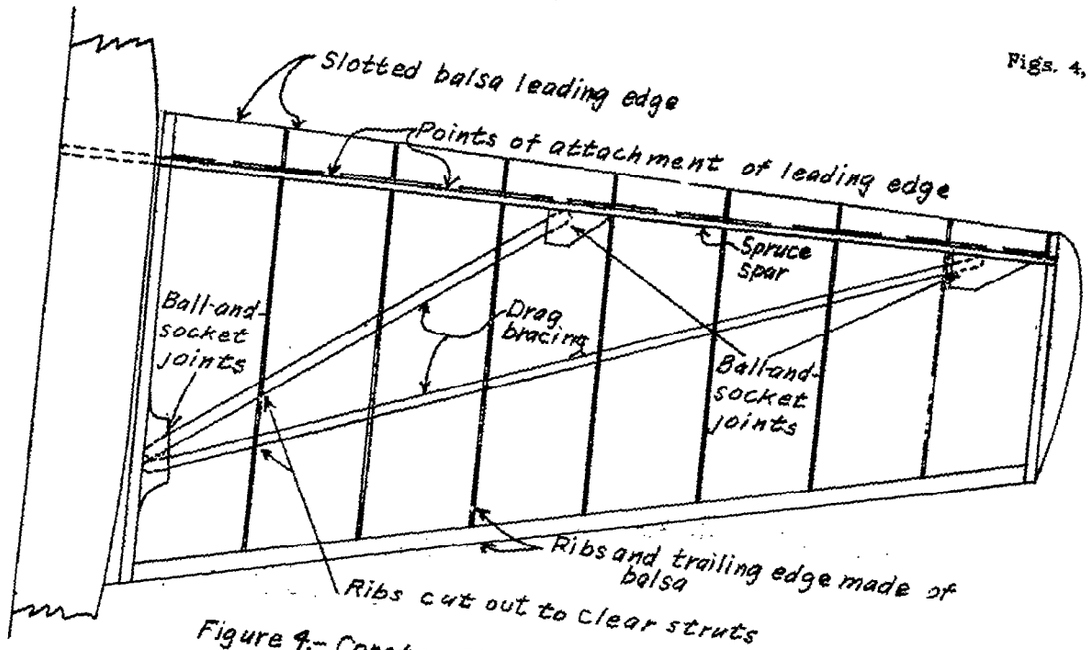


Figure 4.- Construction of flexible wing.

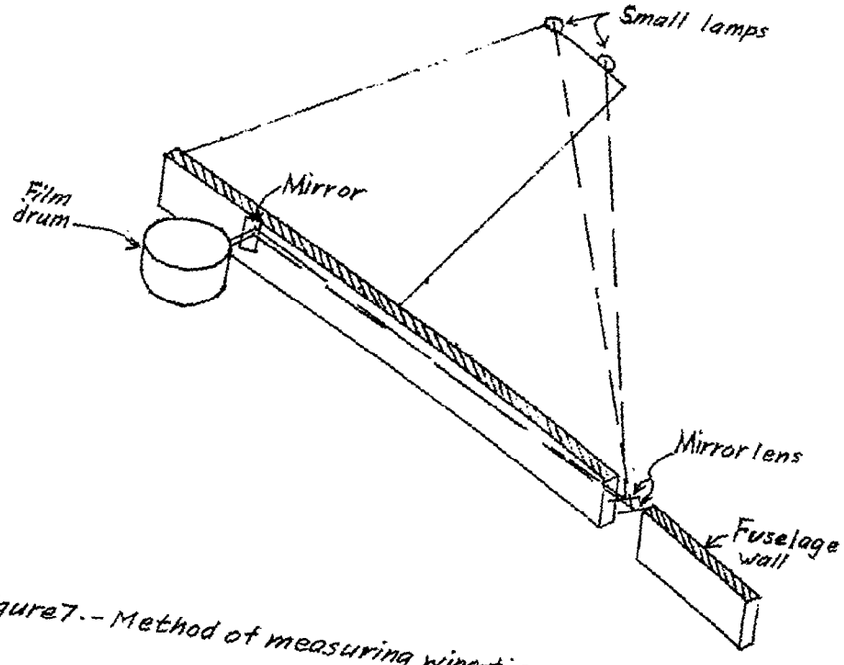


Figure 7.- Method of measuring wing-tip motion.

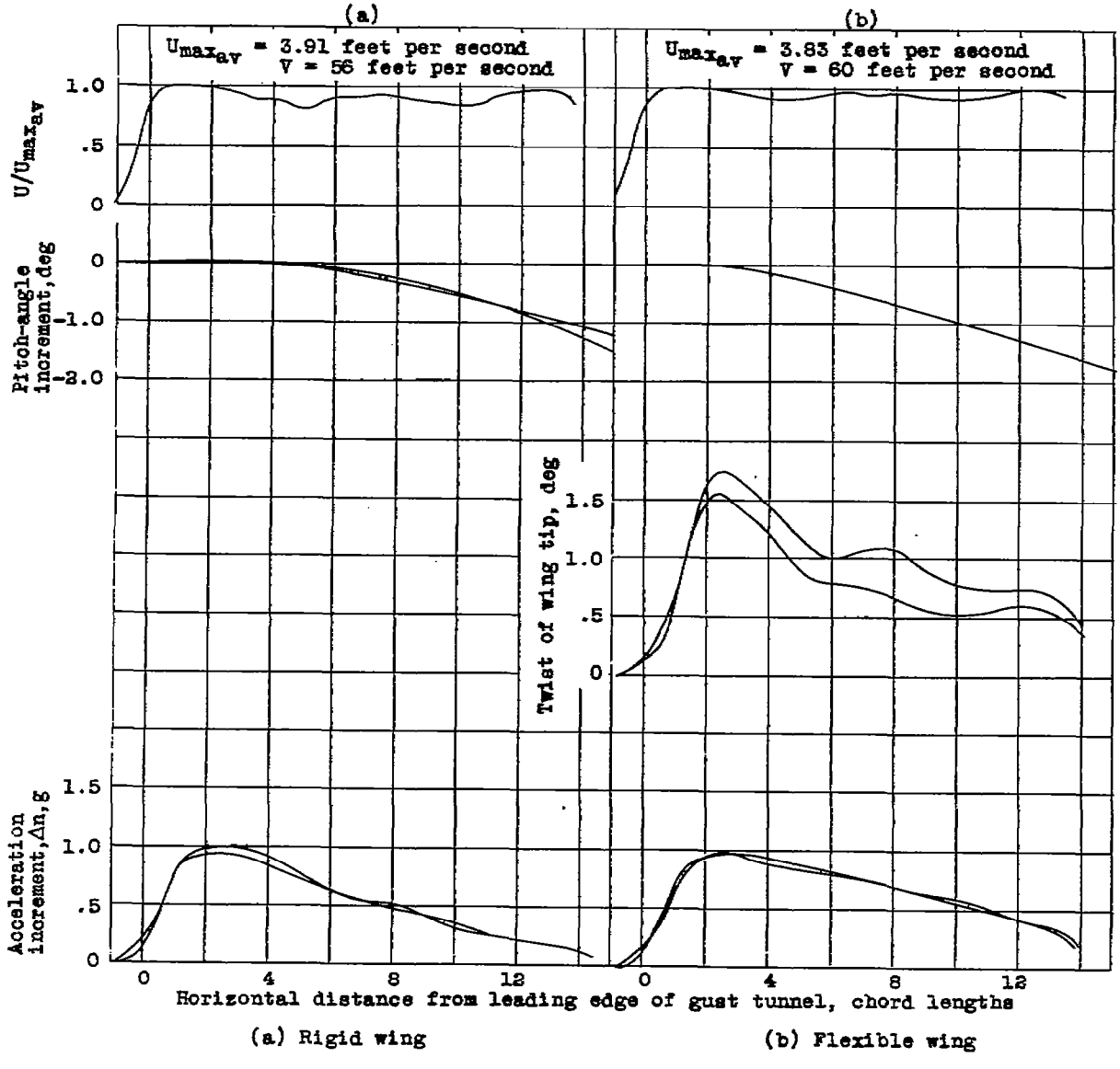


Figure 9.- Histories of events in a 1-chord-length gust(sharp edge).

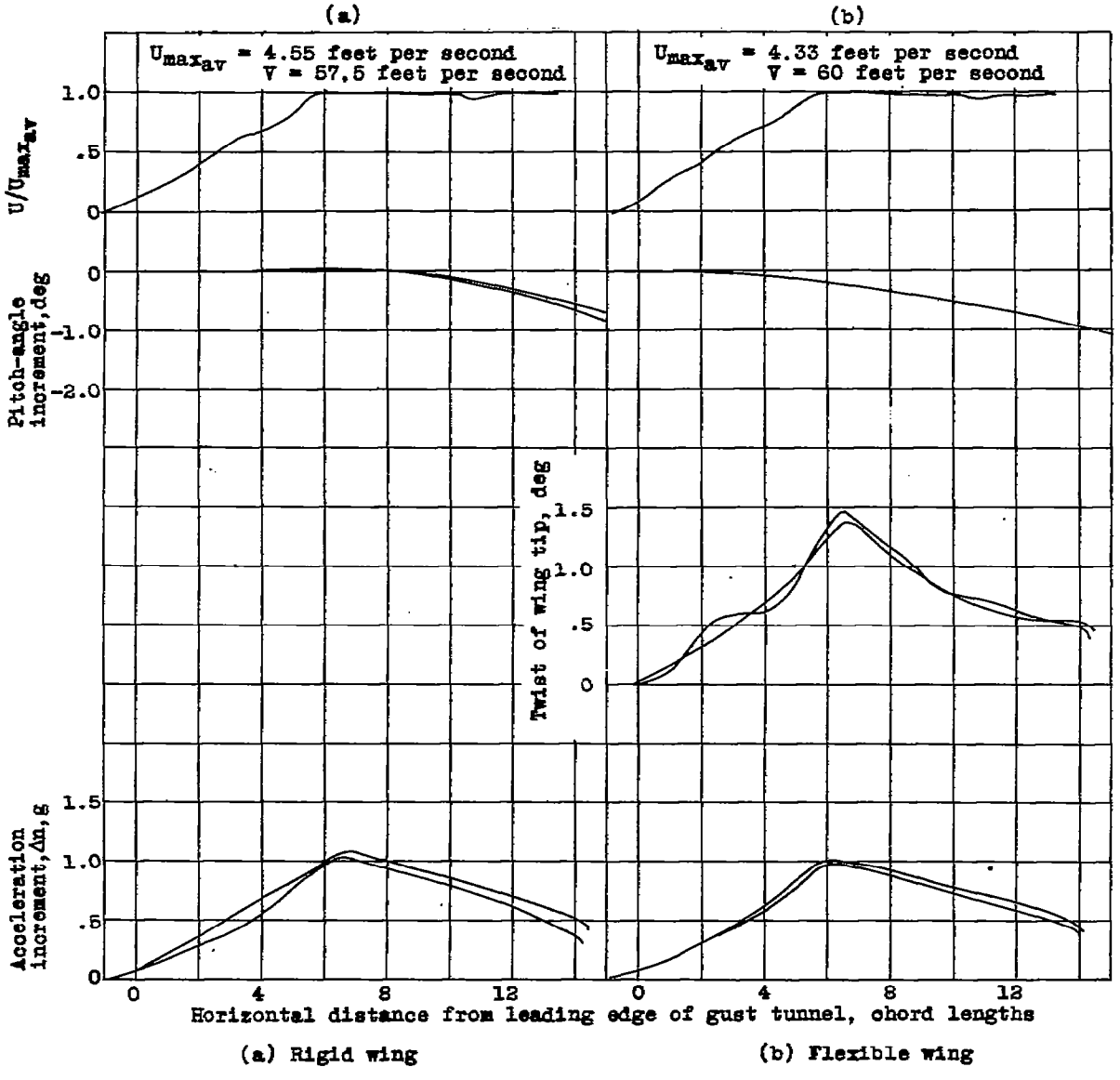


Figure 10.- Histories of events in a 6.8-chord-length gust.

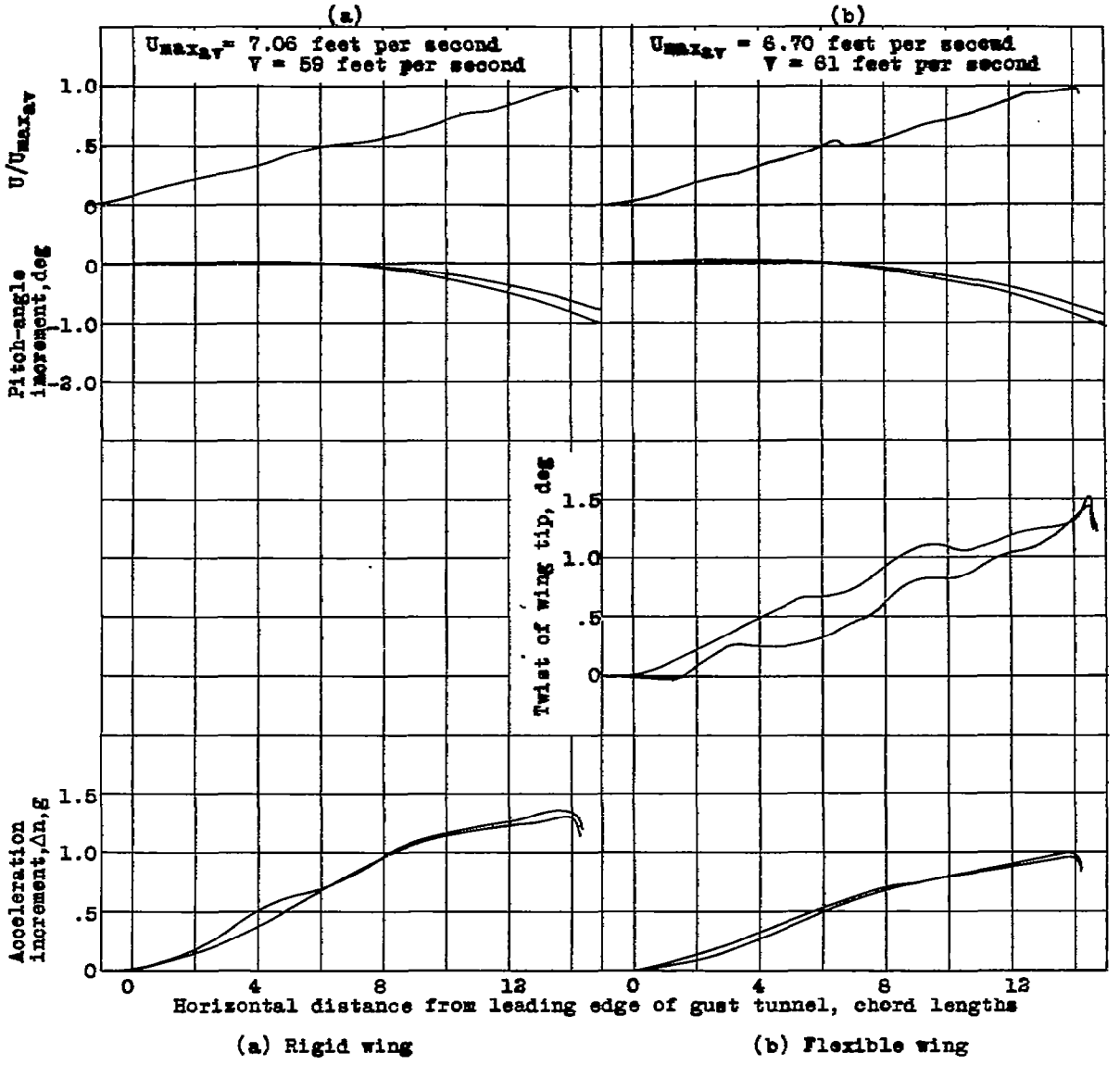
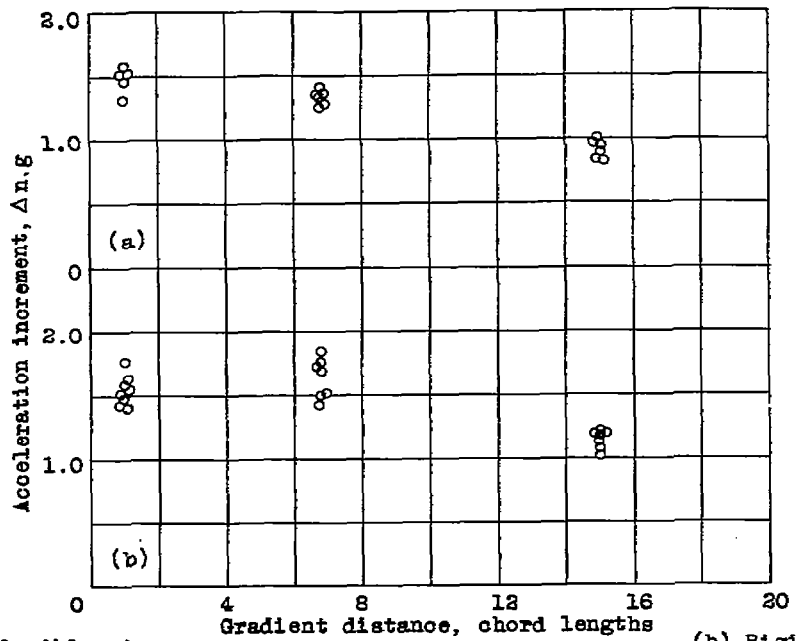


Figure 11.- Histories of events in a 15-chord-length gust.



(a) Flexible wing. (b) Rigid wing.

Figure 12.- Variation at acceleration increment with gradient distance, for $U_{max_{av}}$ = 6.0 feet per second and V = 60 feet per second.

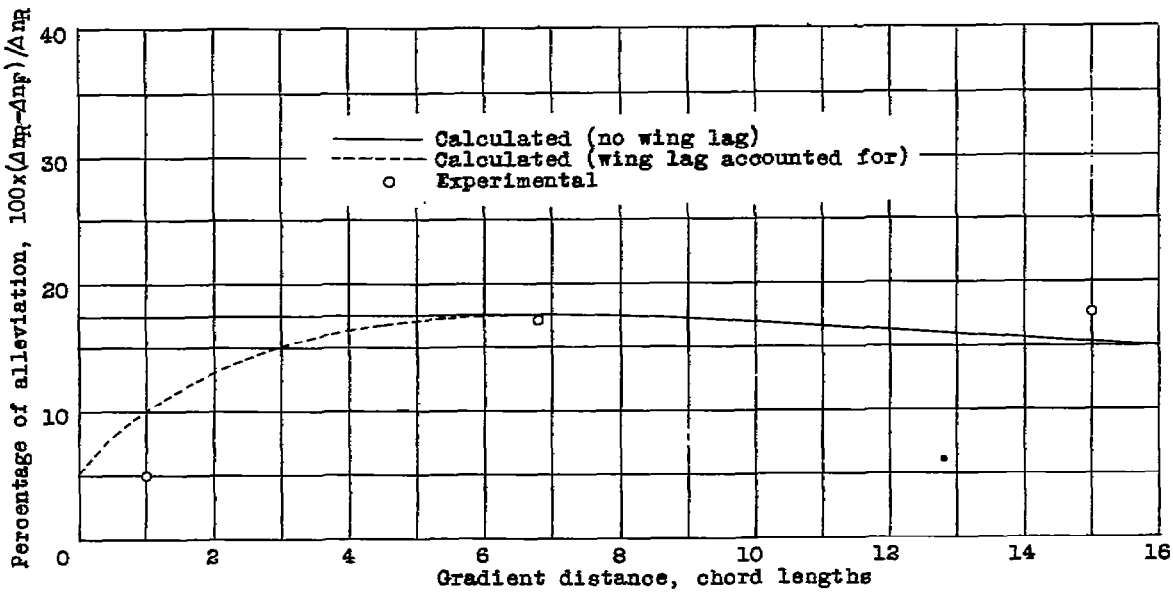


Figure 13.- Variation of wing effectiveness with gradient distance.